18. X-RAY OPTICS AND BEAMLINES

There are several qualitative differences between the femtosecond linac-based source and an electron storage ring source, concerning x-ray optics and beamlines. The first feature is the position or angle correlation of the electron bunch. In the bending magnets, electrons will have a vertical *position*-time correlation, in the undulators, a vertical *angle*-time correlation. These correlations place a requirement on the beamline optics to compress the x-ray pulse or to display the correlation onto a detector. In addition, the average current is low, 10 μA, and consequently, the power radiated by the undulators is also low, typically 0.2 W. None of the high power optical engineering of the third generation synchrotron radiation sources is required. Silicon or fused silica optics can be used without water cooling. The design of the photon stops in the front ends is also simplified. The elimination of the high average x-ray power represents a significant cost savings. Since the x-rays do not have to pass through a storage ring sector arc chamber and front end, the first optic can be close to the source, ~5 m. Finally, a femtosecond laser system will be associated with each beamline.

Briefly, the typical undulator will have the following parameters: length 2 m, λ_u= 1.4 cm and B_{max} =2 T. Flux curves for the 1st to11th harmonics are shown in Figure 18-1. The optimal photon energy range of this insertion device is 1.5 to 8 keV at 2.5 GeV beam energy and 2.3 to 12 keV at 3.1 GeV. Lower photon energies can be conveniently accessed by longer period undulators. In comparison, the present ALS bend magnet beamline 5.3.1 produces fs x-rays with the laser–electron beam modulation technique at an intensity of 10^5 1/(s 0.1% bw). The ALS undulator beamline 6.0 in design will provide fs x-rays at a flux of 10^7 1/(s 0.1% bw). The femtosource undulator delivers approximately 4 orders of magnitude more flux than the laser-electron beam modulation sources.

The shape of the undulator harmonics is modified by the angular correlation in the electron bunches. Figure 18-2 shows the 5th harmonic calculated using the URGENT code [1] in the presence and absence of the angular correlation. The vertical acceptance is increased in order to accept the larger angular divergence of the case with angular correlation. The angular correlation broadens the undulator harmonic, but the peak flux is unchanged. This result can be understood from the fact that each electron is radiating the same spectrum but with a variation of the on-axis direction. Brightness is, however, decreased by the increase in the angular divergence.

Asymmetrically cut crystals may be used as optical elements in the x-ray pulse compression scheme [2,3]. As a result of the different angles of incidence and diffraction, a crystal may be oriented to produce a variable path length across the x-ray beam as shown in Figure 18-3. The optical path length difference Δl for an asymmetrically cut crystal is given by:

$$\Delta l = 2\, \Delta y \sin\theta \sin\alpha / \sin(\theta + \alpha) \qquad (1)$$

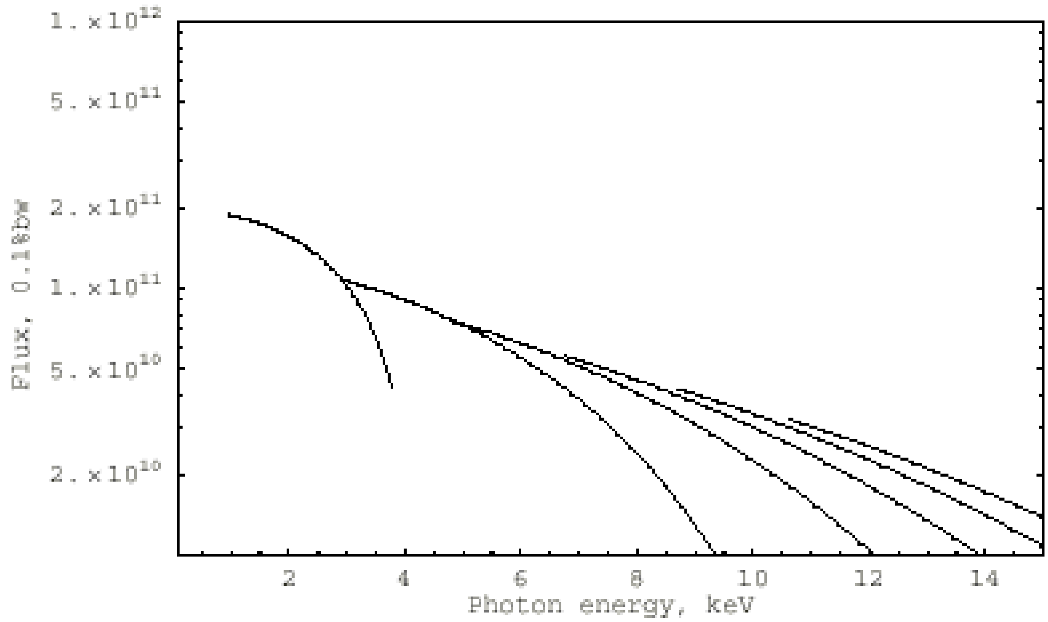

Figure 18-1 Flux of first to eleventh harmonic for the 1.4 cm period undulator calculated for 2. 5 GeV electron beam energy.

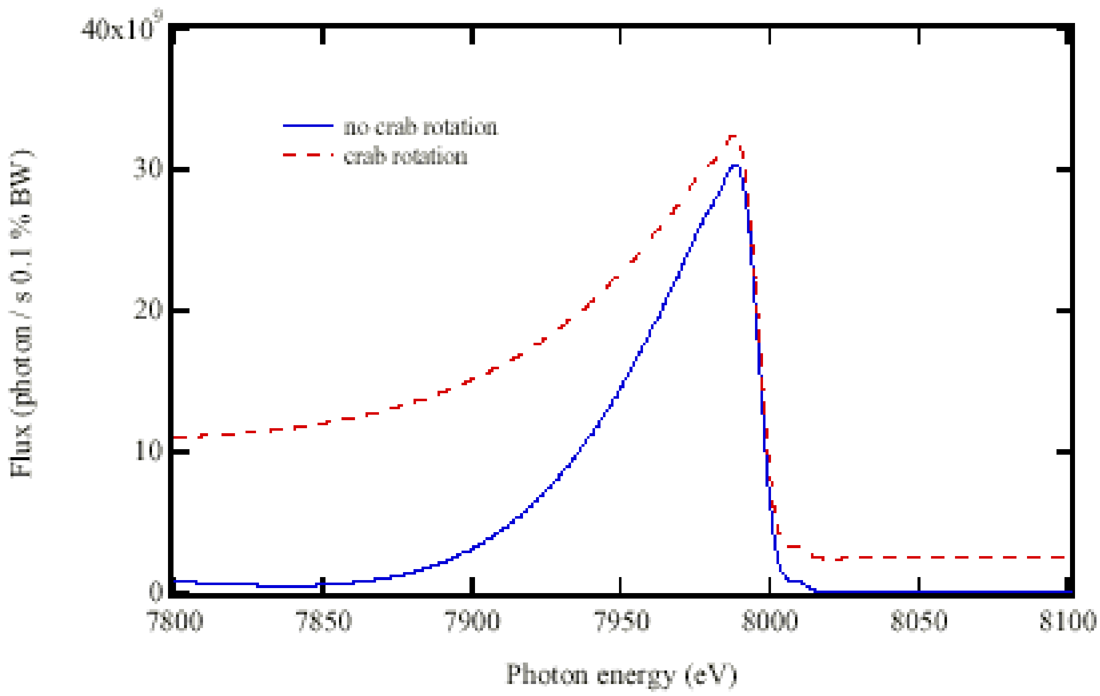

Figure 18-2 The undulator 5th harmonic with and without angular correlation in the electron bunch.

where Δy is the vertical height of the beam at the crystals, θ is the Bragg angle, α is the asymmetry angle between the Bragg planes and the crystal surface. In Table 18-1, a practical example is given of x-ray pulse compression with two asymmetrically cut crystals.

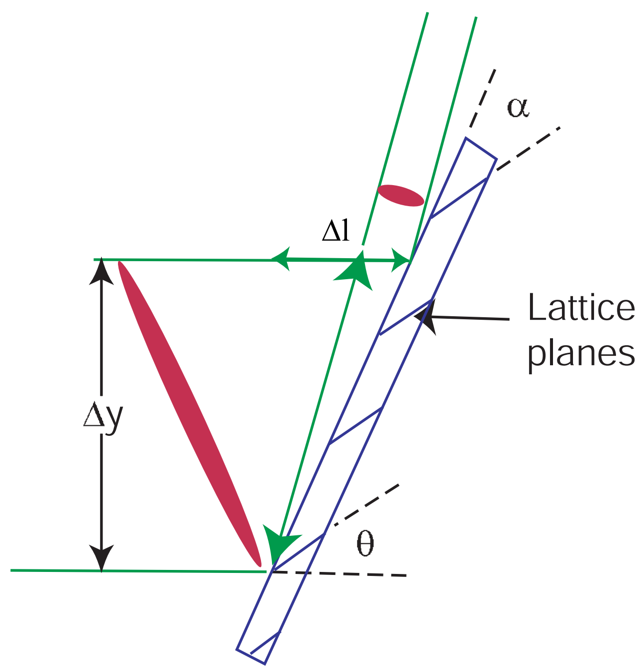

Figure 18-3 Asymmetrically cut crystal with variable optical path length.

Table 18-1 Parameters of two asymmetrically cut crystals for x-ray pulse compression.

Crystals	λ	Δy	θ	α	Δl
Si(111)	1.5 A	3.8 mm	14.309°	-3.5°	0.6 mm (2 ps)

An issue concerns the scanning of the photon energy while maintaining the x-ray pulse compression. As seen in the Eq. 1, the magnitude of the x-ray pulse compression depends upon the Bragg angle θ. Additional rotation of the crystals about the normal to the Bragg planes, ϕ, varies the crystal asymmetry in the diffraction plane. In this way the monochromator photon energy may be tuned while keeping the x-ray pulse compression fixed. For a different purpose, a monochromator with asymmetric crystals and additional rotation axes was built and tested at the Advanced Photon Source [4].

Several factors contribute to the duration of the x-ray pulse. First, the angular correlation permits an x-ray pulse compression given by the ratio of the electron bunch rotation by the electron beam divergence. The divergence of the x-rays also gives a contribution, which increases with $\lambda^{1/2}$. Finally, the penetration of the x-rays into the crystals can broaden the x-ray pulse. But for a low index reflection such as Si(111), this contribution, given approximately by N λ where N is the number of diffraction layers, is small. A pulse duration of 50 fs fwhm is achieved at 8 keV photon energy.

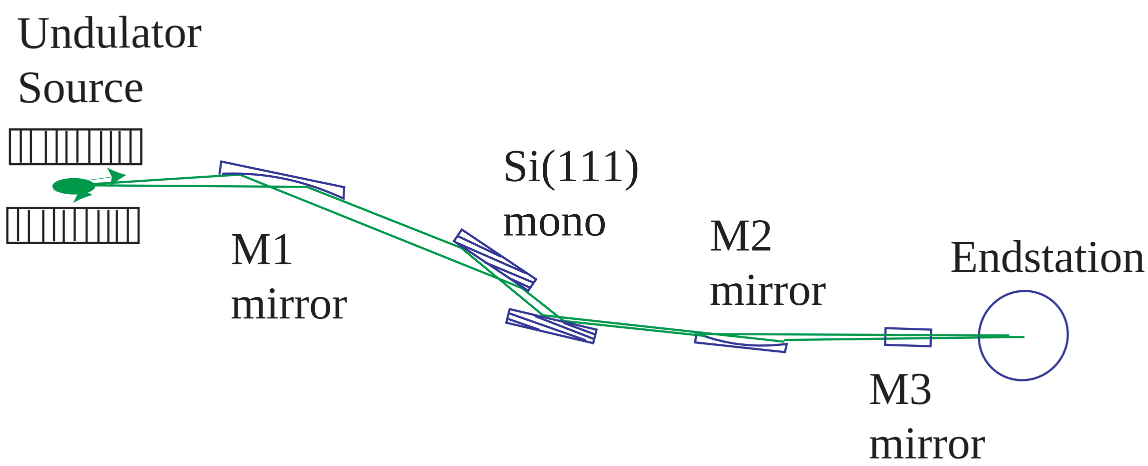

Figure 18-4 Schematic diagram of an undulator beamline with a Si(111) monochromator providing pulse compression.

A schematic layout of an undulator beamline is shown in Figure 18-4. The optical elements are listed in Table 18-2. The source is the electron beam with angular correlation in the small gap undulator. The M1 mirror collimates the x-rays vertically to produce a spatial correlation at a pair of asymmetrically cut Si(111) crystals. These crystals serve as both monochromator and pulse compressor for the x-rays. At 8 keV photon energy the Si(111) crystals have a moderate asymmetry factor b of 1.6 and diffract a bandwidth of 0.9 eV. The M2 and M3 mirrors act as a Kirkpatrick-Baez pair to refocus the beam into the endstation. The distance from the undulator source to the first mirror is short, approximately 5 m, but this is feasible given the low average beam current of the accelerator.

All three mirrors would be polished as planes and bent to a parabolic or elliptical figure. The tolerance of 1 µrad slope error for the M1 and M2 mirrors is at, but not beyond the current state-of-the-art in optical fabrication. The dimensions of the optics, including the length of the M1 mirror, are within the present capabilities of the synchrotron optical vendors. The length of the beamline is 12 m. The photon energy range is from 2 to 11 keV.

Raytracing of the undulator beamline has been performed using the XOP software available from the European Synchrotron Radiation Facility [5]. Spot diagrams of the endstation focus are displayed in Figure 18-5. The source dimensions are 390 µm (h) x 20 µm (v) and divergences are 50 µrad (h) x 750 µrad (v) total width of the flat-top distribution. The rotation of the electron bunch is included in the vertical divergence. The focus dimensions are 48 µm (h) x 55 µm (v) and divergences are 0.5 mrad (h) x 0.3 mrad (v) fwhm. The x-ray spot size in the endstation is well matched to a small focal spot for the laser used to excite the sample. The divergence of the

Table 18-2 A list and description of the optical elements of the undulator beamline.

	Type	Coating and blank material	Dimensions (mm)	Radius (m)	Incidence angle(°)	Distance from source (m)
M1	Plane parabolic mirror	Pt-coated silicon	650 x 60	1430	89.6	5
X1, X2	Crystal	Silicon (111)	60 x 60	∞	75.6912 $\alpha = -3.5$	6
M2	Plane parabolic mirror	Pt-coated silicon	300 x 25	1430	89.6	7
M3	Plane elliptical mirror	Pt-coated silicon	200 x 20	339	89.6	10.667
Endstation						12

x-rays in the endstation is acceptable for spectroscopy and for some x-ray diffraction experiments. At a particular beamline it would be possible to reduce the divergence at the sample with a corresponding increase in the spot size.

At a conceptual level a bend magnet beamline has also been considered. The source is a bend magnet source with a vertical position-time correlation. Here, the coordinate-time correlation of the radiation is used without compressing the x-ray pulse for observations at different time delays. Two Kirkpatrick-Baez mirrors focus the beam onto a thin sample in the transmission geometry. A Varied Line Spacing (VLS) grating spectrograph disperses and focus the x-rays onto a position sensitive detector, where one dimension represents photon energy and the other time. The individual time slices are imaged at the detector. The photon energy range covered would be 100 eV to 2 keV. The flux of the bend magnet is less than the undulator source, however entire absorption spectra could be obtained simultaneously. Circular polarization could be provided for magnet samples by accepting radiation above or below the accelerator plane.

Further work is needed in quantitative evaluations of pulse broadening in pulse compression crystals. The detailed undulator beamline design will need to accommodate to space constrains of the shield wall.

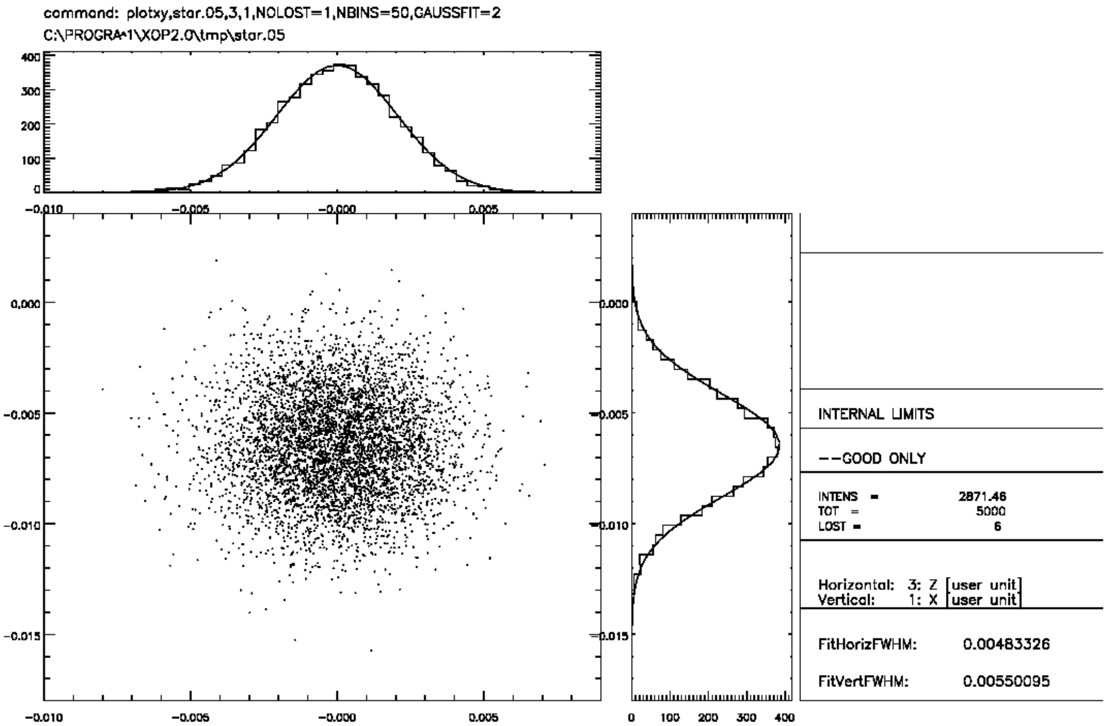

Figure 18-5 Focus dimensions at the endstation of the undulator beamline. Dimensions in cm.

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